Complexity and the Grid

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RD4 Seminar
April 8th 2024

The power grid is a complex and critical system

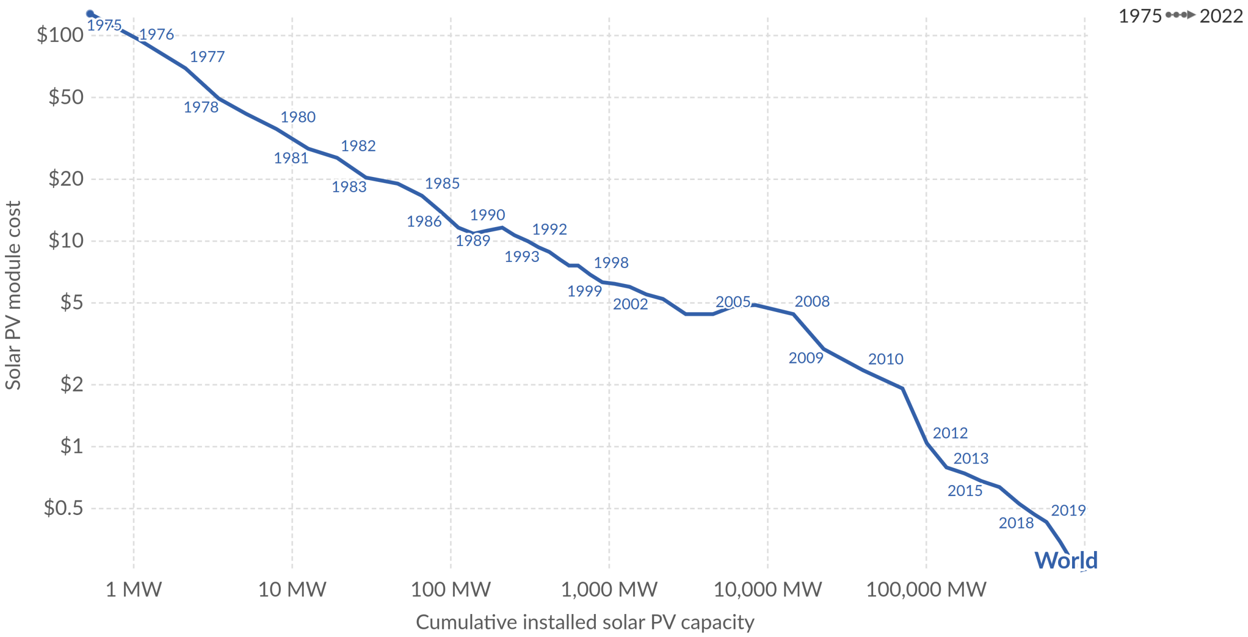
NASA Earth Observatory
Black Marble

Complexity and the Grid

On the production side, solar is taking over.

Solar (photovoltaic) panel prices vs. cumulative capacity

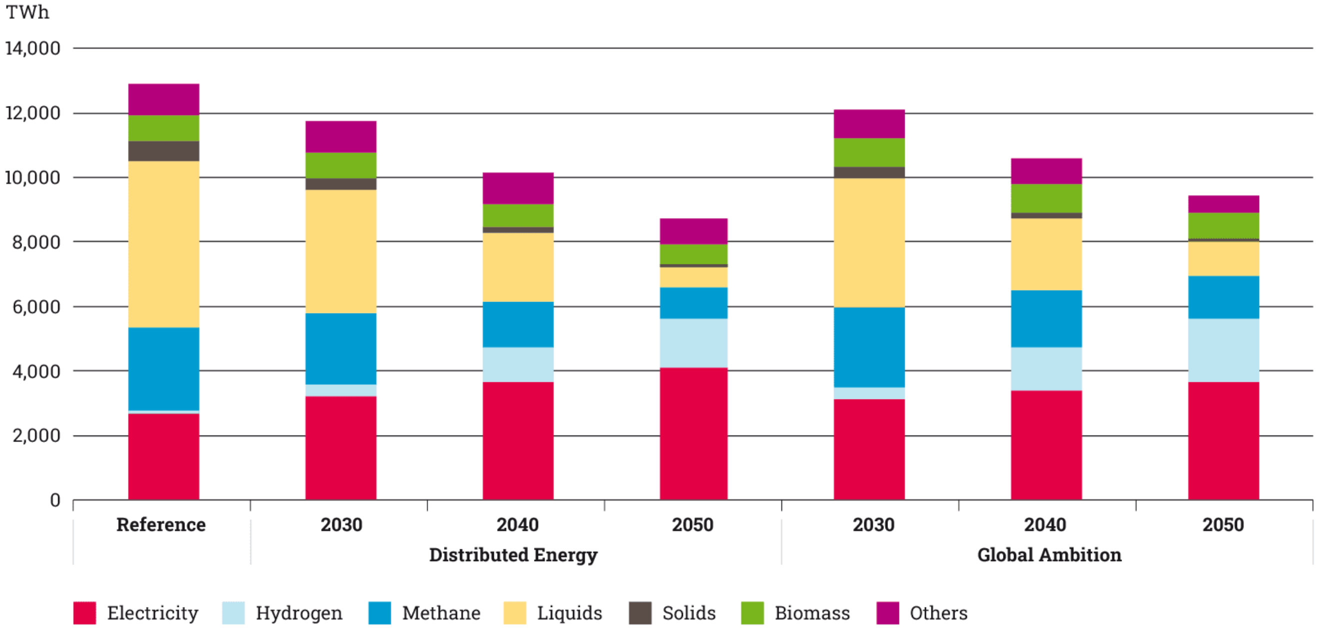
This represents the learning curve for solar panels. This data is expressed in US dollars per Watt, adjusted for inflation. Cumulative installed solar capacity is measured in megawatts.



Data source: International Renewable Energy Agency (2023); Nemet (2009); Farmer and Lafond (2016)
Note: Data is expressed in constant 2022 US$ per Watt.
OurWorldInData.org/energy | CC BY

https://ourworldindata.org/grapher/solar-pv-prices

Electrification of energy consumption underpins the decarbonization of our societies:

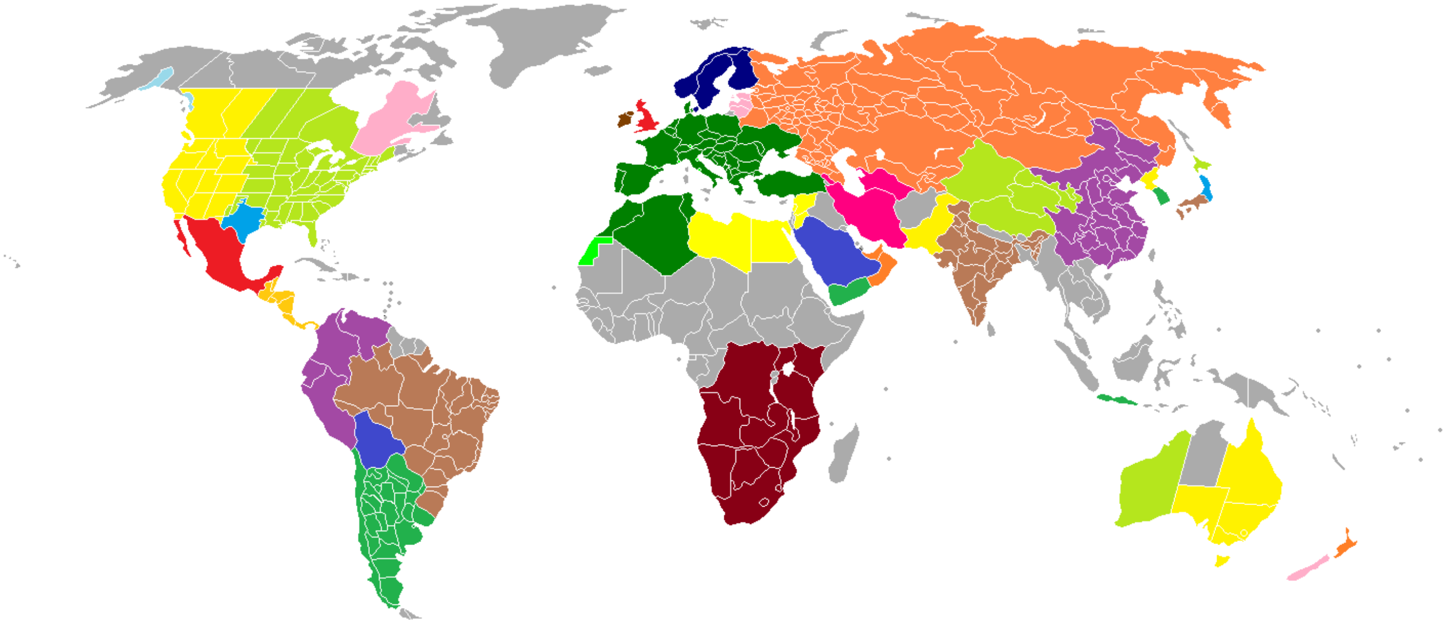


ENTSO-E 2022 Scenario report

Complexity and the Grid

The reliable flow of energy relies on a self-organized synchronous state that extends to continental scale.

The system evolves at time scales from milliseconds to decades.



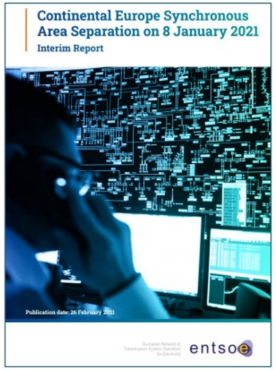
Things can and do go wrong with this.

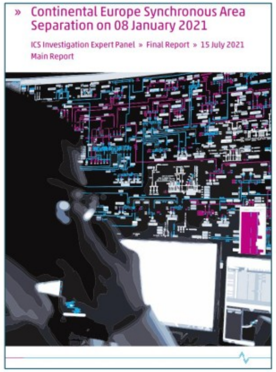
e.g. cascading failures

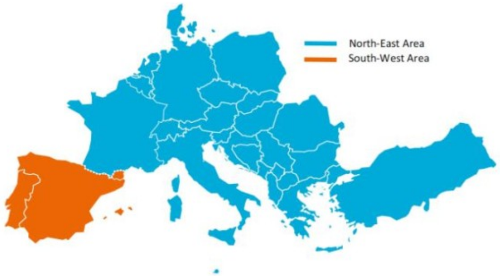
Teilnetzbildungen

Aktuelle Großstörung

- System Split am 8. Januar 2021
- System Split am 24. Juli 2021







Complexity and the Grid

We are in the middle of the most meaningful restructuring of our economies and societies since industrialization/globalization.

Without solving all grid issues in the next 15 years, there will be no carbon neutral economy in 2050.

(Ireland is currently capping RES at 70%)

Complexity and the Grid

Many electrical and mechanical engineers and control theorists are working to do just that.

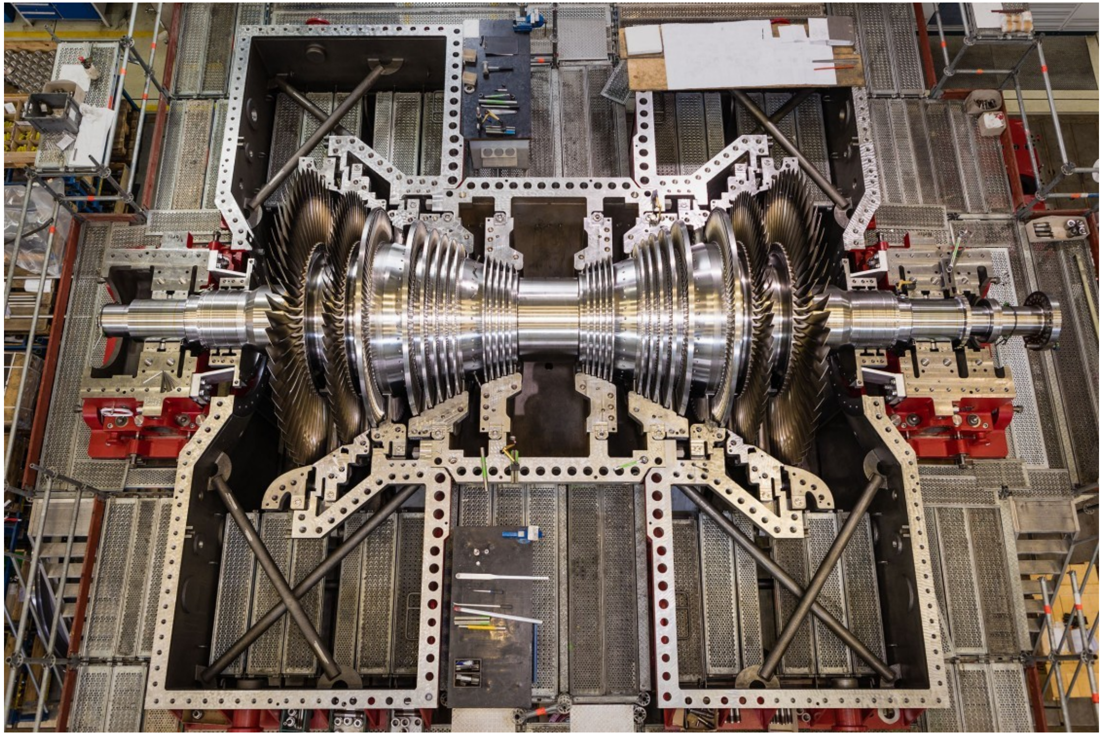
Where does Complexity Science come in?

Where are our approaches complementary to domain expertise and how can we contribute?

What challenges are interesting for us?

Complexity and the Grid

Challenge: New actors.



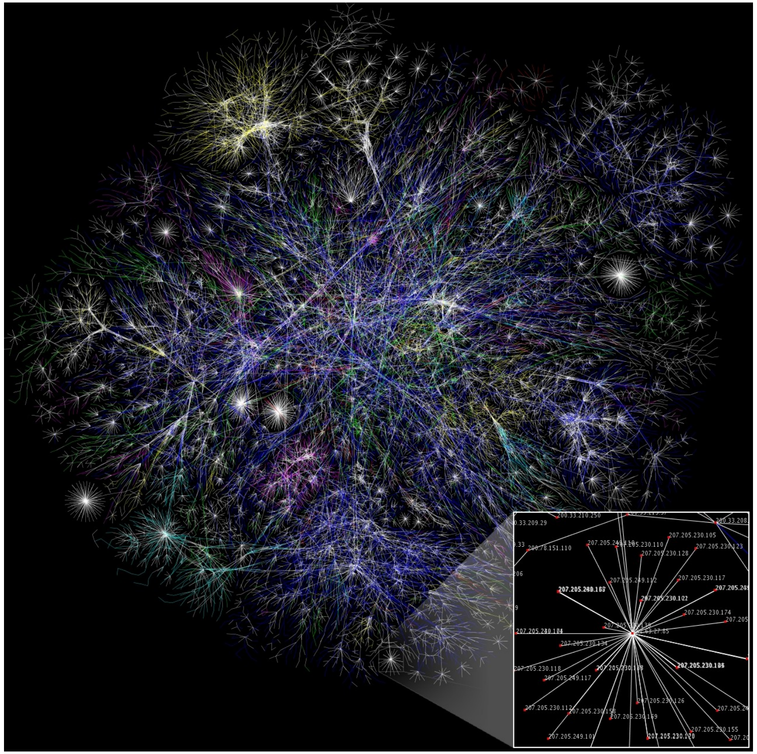
We are replacing thousands of heavy rotating turbines with well understood dynamics by millions of programmable inverters with a wide variety of designs and behaviors.

Complexity and the Grid

Challenge: New actors.

→ Systems first modeling

Network Science:
Study the role of connectivity in shaping system behavior.

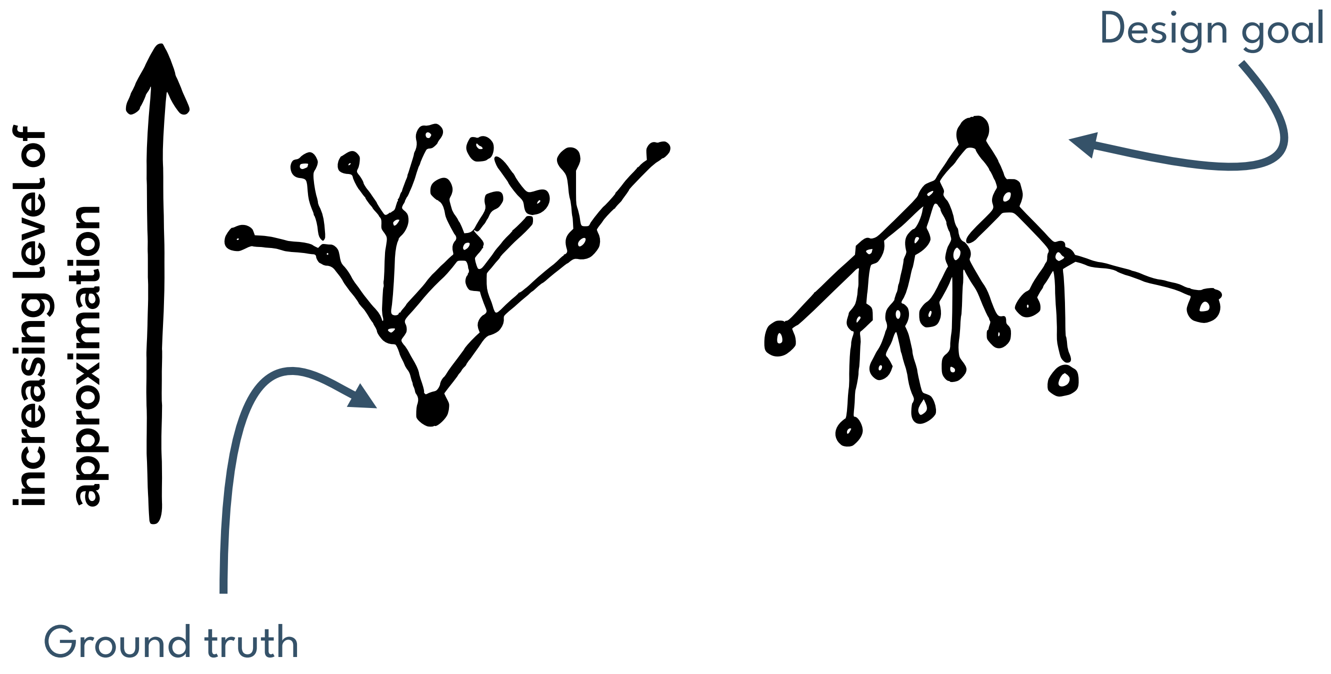


https://en.wikipedia.org/wiki/Network_science#/media/File:Internet_map_1024.jpg CC BY 2.5

Complexity and the Grid

Challenge: New actors.

→ Systems first modeling of the components:

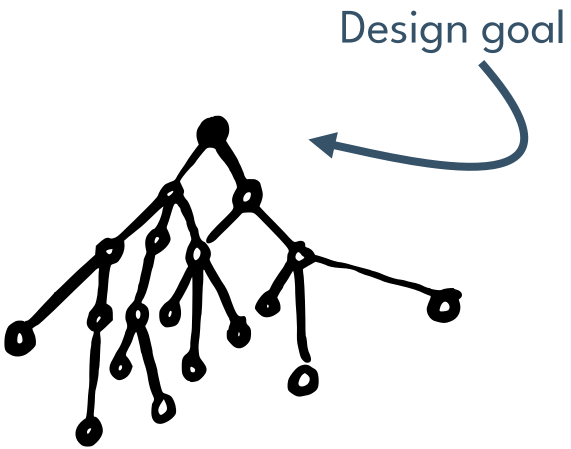


Challenge: New actors.

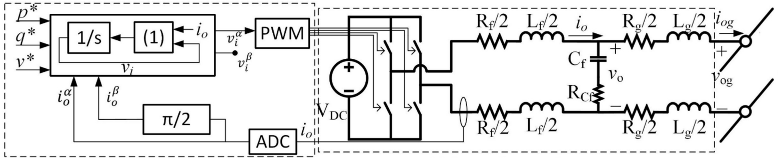
→ Beyond connectivity: Systems first modeling of the components!

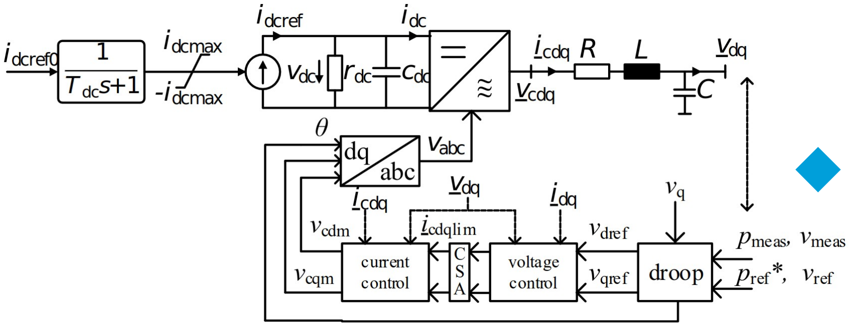
Everything is built to ensure the proper function of the overall system.

From this we can derive certain functional requirements and design goals for the components. We then systematically exploit these to get a space of plausible behaviors.



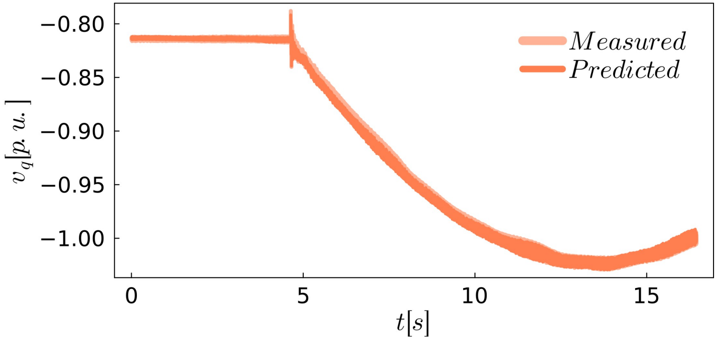
Complexity and the Grid

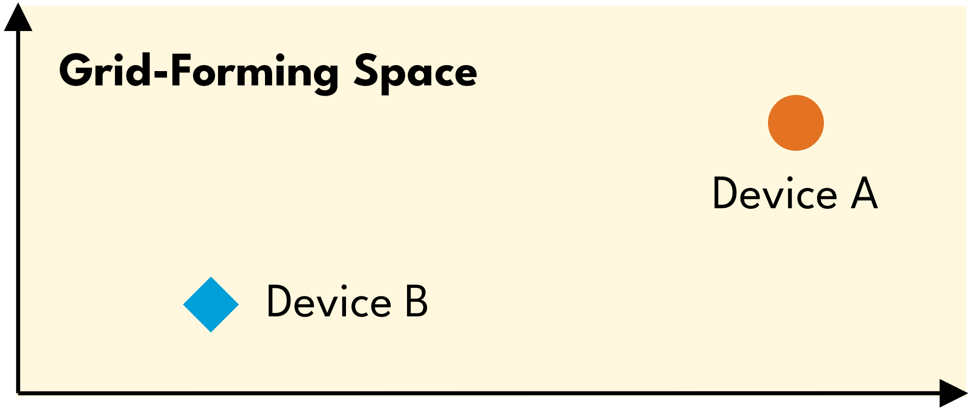




Device A

Device B





Complexity and the Grid

Challenge: The system is going to be orders of magnitude larger. Dynamical stability needs to be maintained without constant monitoring.

Complexity and the Grid

Challenge: Dynamical stability needs to be maintained without constant monitoring.

→ Understand stability properties using probabilistic and mathematical approaches.

Mathematical: Well parametrized space allows for universal statements on stability and robustness.

For example, we have a very nice new theorem for the linear stability of adaptive networks.

… but it doesn't apply to our model class :(

Corollary 1 (Generalized small phase theorem, Network Version). *Consider a network with sets of vertex and edge transfer matrices $T^n_{ve}(s)$ and $T^m_{ev}(s)$, and edge-vertex coupling given by B. Denote the projector onto the space orthogonal to the kernel of $B^\dagger$ as P^B. For each n, let $T^n_{ve}(s)$ be semi-stable frequency-wise semi-sectorial with $j\Omega$ being the union of the set of poles on the imaginary axis. For each m, let $T^m_{ev}(s) \in \mathcal{RH}_\infty$ be frequency-wise sectorial. Then the interconnected systems $(P^B \bigotimes_n (T^n_{ve}) P^B) \# (B \bigotimes_m (T^m_{ev}) B^\dagger)$ is stable if*

$$\max_n \overline{\phi}(T^n_{ve}(j\omega)) - \min_n \underline{\phi}(T^n_{ve}(j\omega)) < \pi \tag{411}$$

$$\max_m \overline{\phi}(T^m_{ev}(j\omega)) - \min_m \underline{\phi}(T^m_{ev}(j\omega)) < \pi \tag{412}$$

Complexity and the Grid

Challenge: Dynamical stability needs to be maintained without constant monitoring.

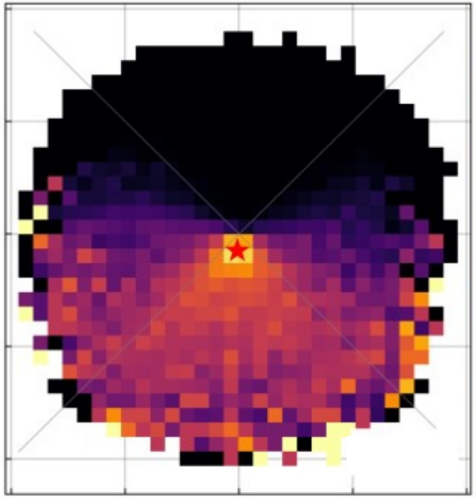
→ Understand stability properties using probabilistic and mathematical approaches.

Probabilistic: Replace mathematical analysis with more modeling!

Using a stochastic model of perturbations and scenarios, measure the probability that the system survives.

→ Study the parameter space…

Grid-Forming Space



Complexity and the Grid

Challenge: Dynamical stability needs to be maintained without constant monitoring.

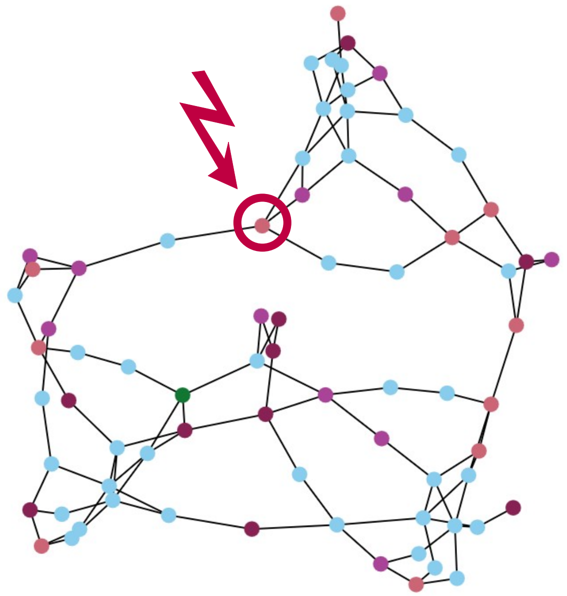
→ Understand stability properties using probabilistic and mathematical approaches.

Probabilistic: Replace mathematical analysis with more modeling!

Using a *stochastic model of perturbations* and scenarios, measure the probability that the system survives.

→ ... or systematically vary the *stochastic model* to study the properties of the system.

E.g. Faults localized at one node:



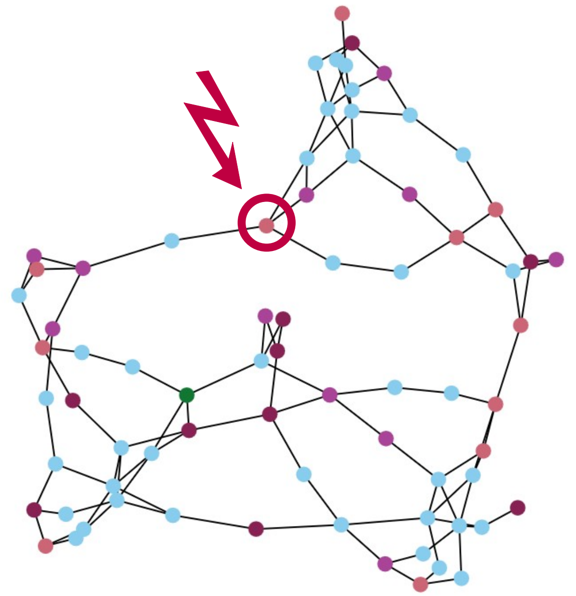
Complexity and the Grid

Challenge: What actually determines the resilience and stability of a grid?

→ ... or systematically vary the stochastic fault model to study the properties of the system.

→ Find structural properties and dynamical parameters that strongly influence / predict where the grid is stable and where it is vulnerable.

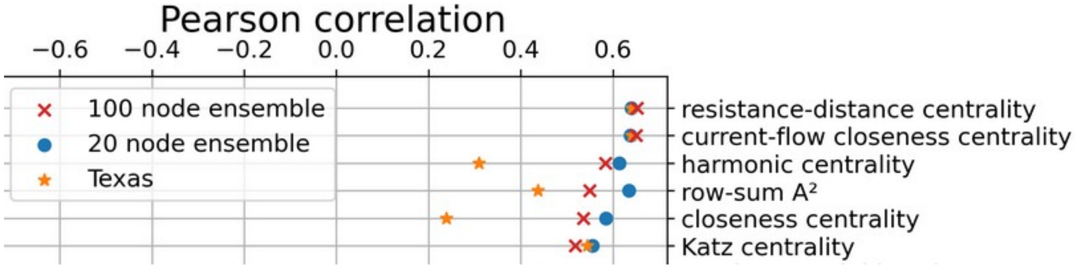
E.g. Faults localized at one node:



Complexity and the Grid

Challenge: What actually determines the resilience and stability of a grid?

→ Network Science approach: Network measures that correlate.



→ Machine Learning: Directly predict from the graph structure.

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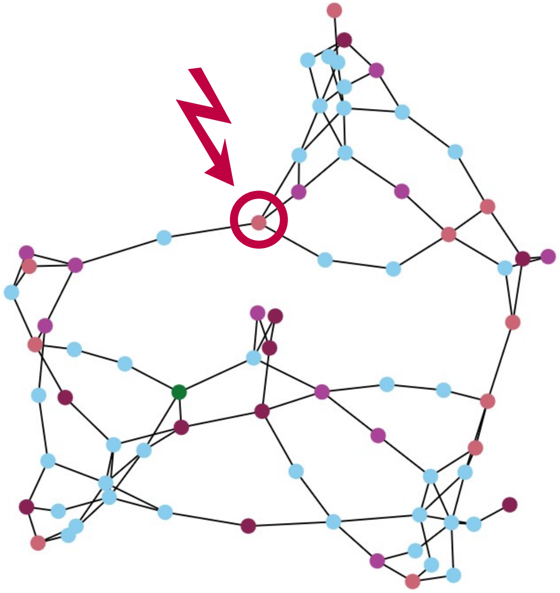

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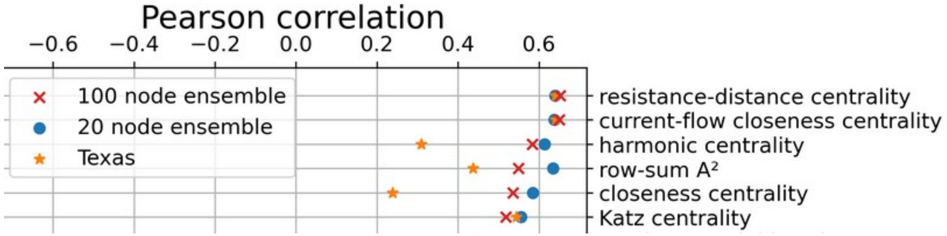

→ Machine Learning: Directly predict from the graph structure using Graph Neural Networks.

For Basin Stability the latter generalizes better! Seems to capture the causality rather than just correlation.

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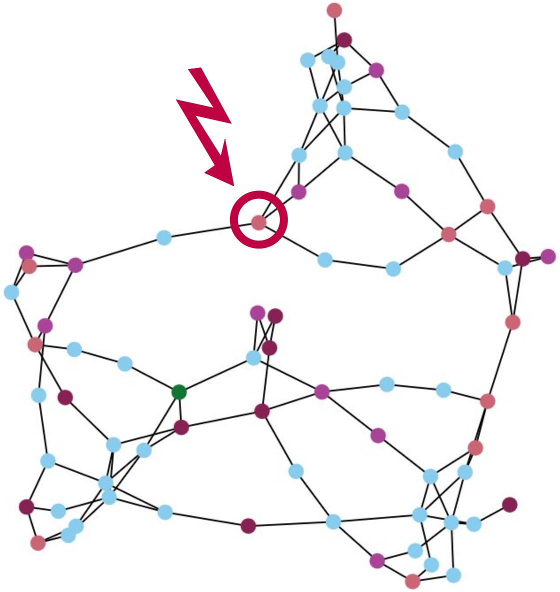


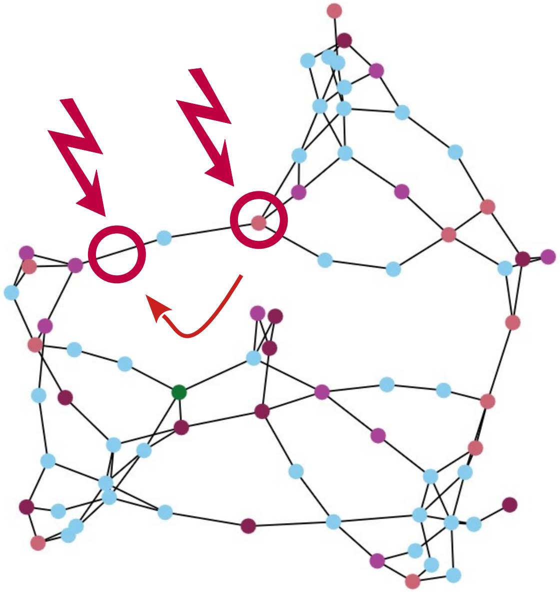
Complexity and the Grid

Challenge: What actually determines the resilience and stability of a grid?

→ Really counterintuitive results when we look at the systemic response to localized failures!

Making individual nodes more robust can make the overall system more fragile.

Cascading failing of nodes and edges:

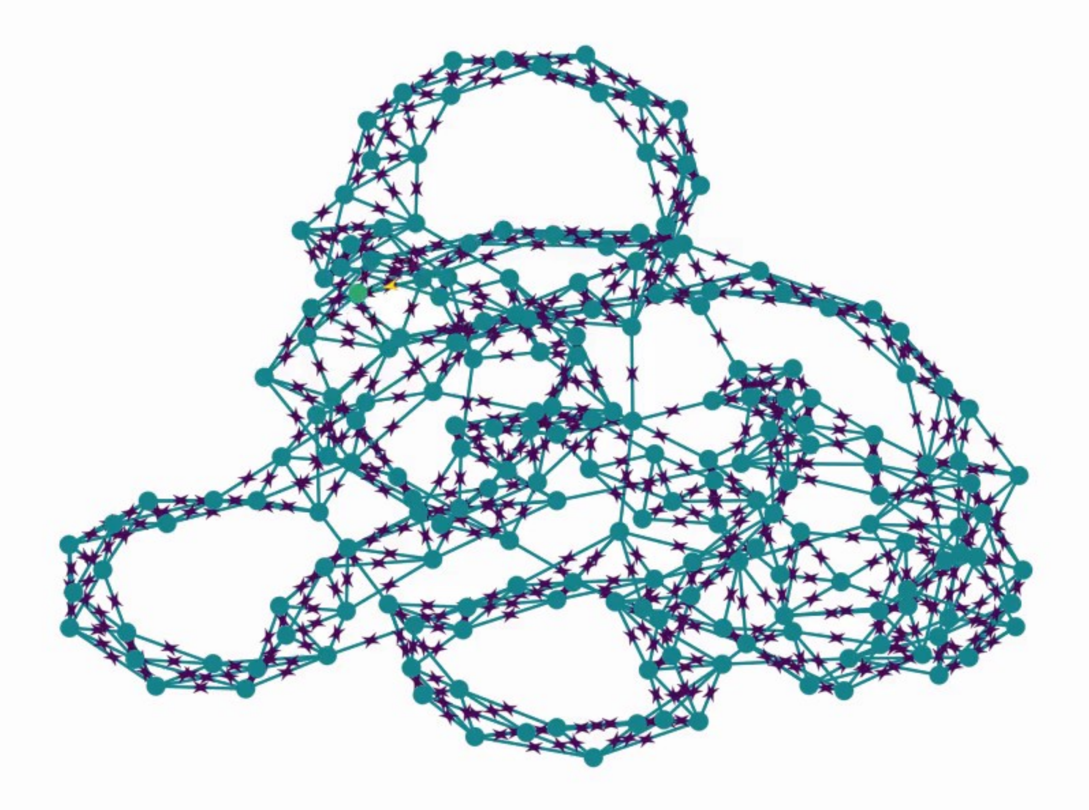


Complexity and the Grid

Intermezzo: Graph Neural Networks.

Interestingly Graph Neural Networks are essentially discrete dynamical systems on the graph. We can use our methods to study them, or use our knowledge of network dynamics to design new architectures.

I believe understanding how they come to predictions could benefit from a dynamical systems eye.



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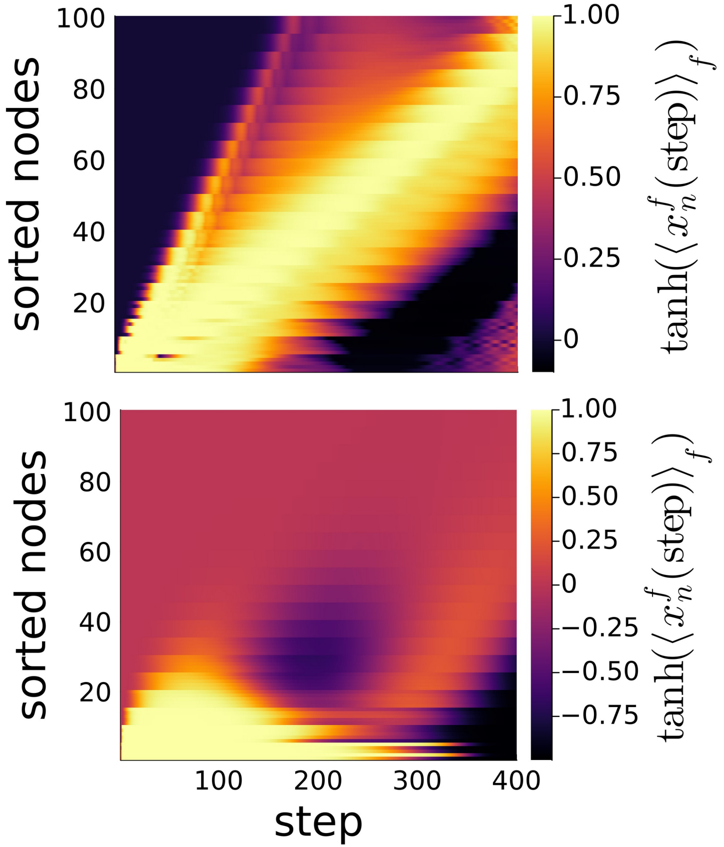
Our Architecture:

Conventional MPNN:



The power grid is a complex system

Challenge: Most of the time, nothing happens.

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→ Use MCMC to systematically generate situations in which things do happen.

1) Propose a change in the system.
2) Measure if it look like more/less is happening.
3) → Accept/Reject change with temperature dependent probability.
4) Repeat

Complexity and the Grid

Challenge: Most of the time, nothing happens.

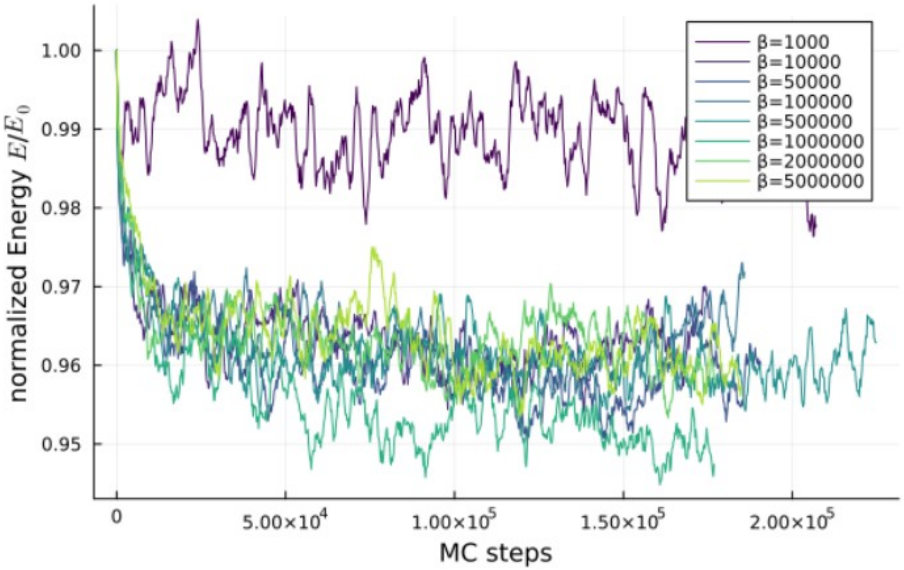
→ Use MCMC to systematically generate situations in which things do happen.

E.g. Feed in patterns or topologies with particularly bad/good stability properties.

We have also used this approach in ride sharing and in the pandemic context.

Its pretty tricky...

... but its how we can find non-obvious compound extremes that might pose a real danger.



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→ Be creative generalist complexity scientists.

Complexity and the Grid

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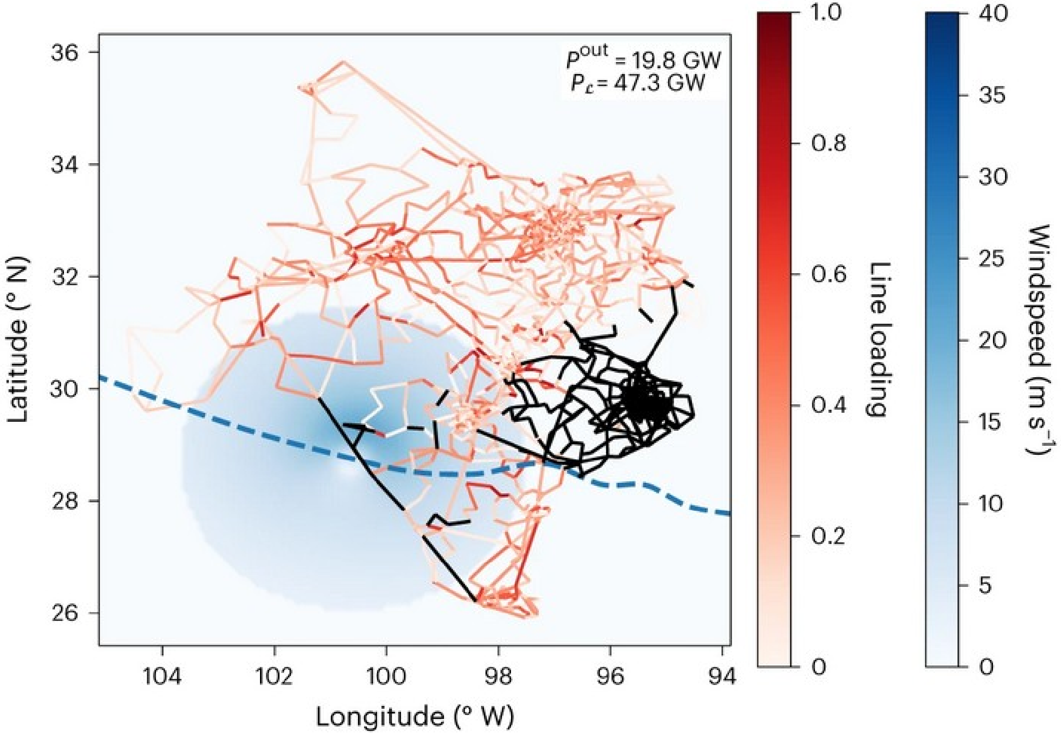
E.g.: Both cascade and storm models existed, but we figured out how to put them together.

... and we can reveal systemic properties again.

(And we don't know how to do it for other extreme events yet!)



Complexity and the Grid

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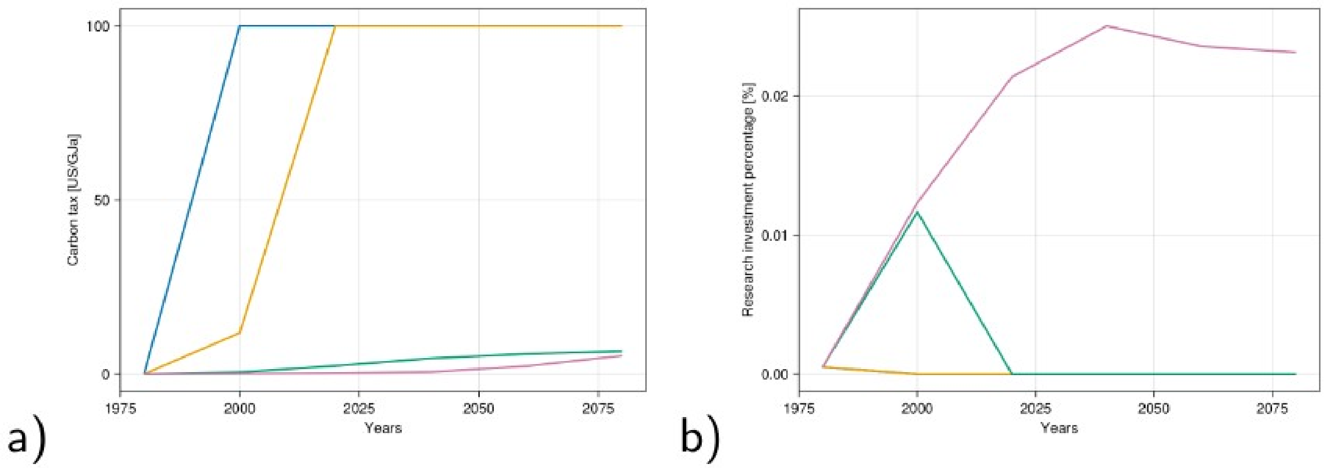
On the longest time scales: Many things are done very adhoc.

For example: Political difficulty of implementing the energy transition.



Complexity and the Grid

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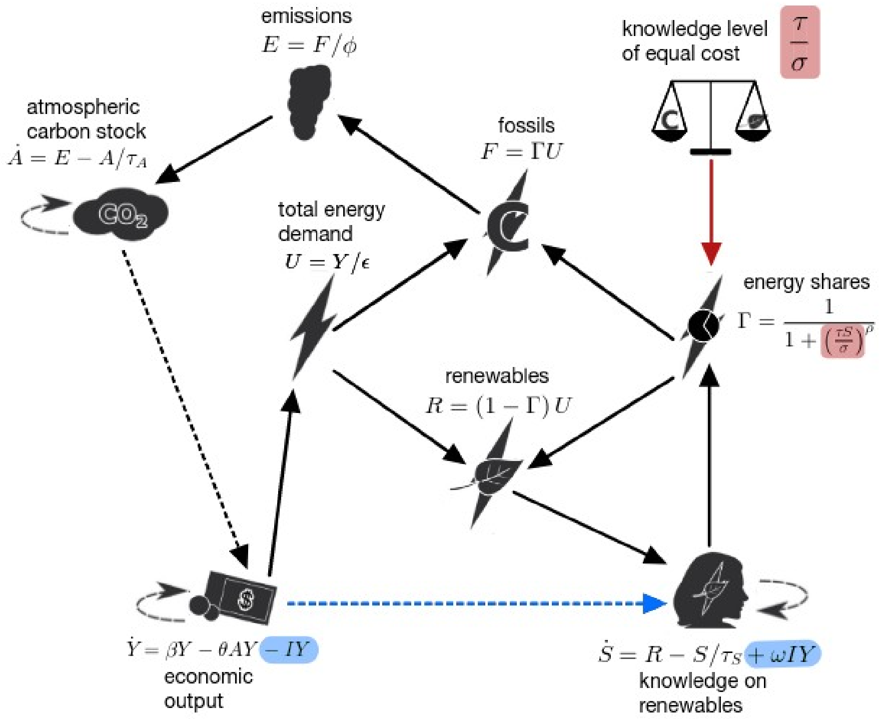
E.g.: Policy mix and political feasibility



Complexity and the Grid

Challenge: Many interactions and systems are not (yet) modeled.

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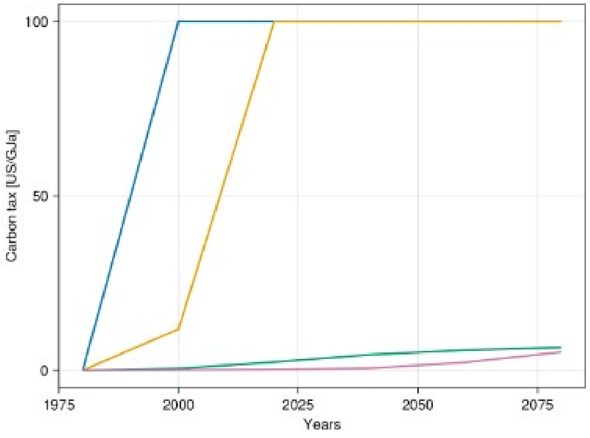
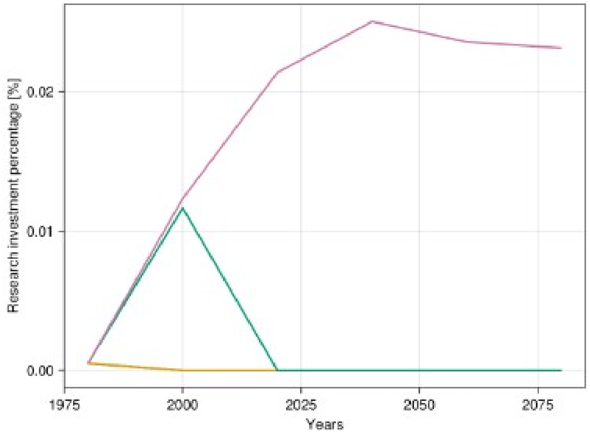
By incorporating knowledge dynamics, several policies and a "political cost" we see trade offs of different policy mixes:



a)

Carbon Tax



b)

Research Investment

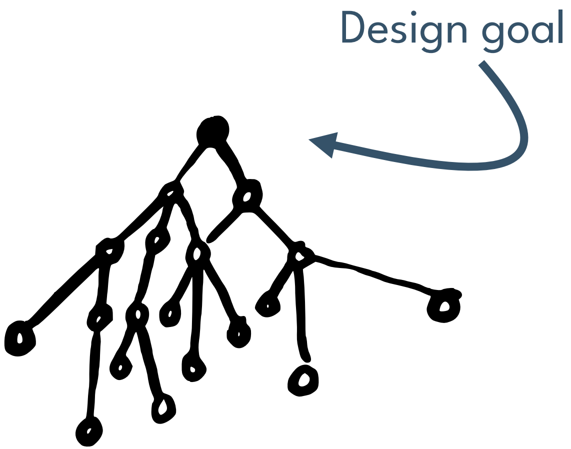
Complexity and the Grid

So what does a complexity scientist/theoretical physicist do in the energy transition:

Bring a systems first view.
Models that do things differently and allow you to do different/new things.
Have a good toolbox for studying systemic properties and discovering what causes them.

Concrete methods that I believe can be interesting elsewhere:

Probabilistic study of systemic properties
MCMC
AI for Graph Data
Component modeling from design goals



Thank you